Distribution of zeolitic soils in India

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Calcium-rich zeolites control naturally occurring chemical degradation in the black soils (Vertisols and their intergrades). With the help of modern tools such as remote sensing, geographic information system, soil database, geological information, topography and other related datasets, an attempt was made to update the distribution of zeolitic soils in India. To ascertain the presence of Ca-rich zeolites in soils, mineralogical information was generated using X-ray diffraction techniques for the selected soils from the Indo-Gangetic Plains and the black soil region (BSR). The zeolitic soils are mostly confined in the pediments (sloping regions of the upland) of the Deccan plateau in BSR, although a few are also found along the valley floor. The IGP, on the other hand, hosts the zeolitic black soils along the drainage channels in the valley floor where the basaltic alluvium deposited the smectite and clay-rich sediments. The study indicates Ca-rich zeolitic soils in India to occupy an area of ~2.8 m ha, of which BSR and IGP constitute ~92% and ~8% respectively. The zeolites are mostly concentrated in the drier tracts of the country and help in maintaining soil health against natural soil degradation. While the occurrence of Ca-rich black soils in BSR was known, those in the IGP are new findings. With the help of the available information, we have generated state-of-art information approximation map on the distribution of Ca-rich zeolites in Indian soils.

Keywords: Black soils, calcium-rich zeolites, mineralogical information, soil map.

PRESENCE of calcium-rich zeolite has been reported to enrich soil exchange complex with calcium ions to improve soil drainage. Improvement of physical properties in zeolitic soils and hence more organic carbon sequestration help in the formation and persistence of organic matter-rich, soft, clayey and smectitic, brown forest soils (Mollisols) even in humid tropical climate. Presence of zeolite in semi-arid tropics inhibits soil degradation in spite of the formation of pedogenic calcium carbonate[1–4]. Zeolites have been reported to have a selectivity for K^+ and NH_4^+ ions. In view of this, K adsorption and supply in the soils may be contributed by zeolites[5,6]. Petrographic and scanning electron microscopic (SEM) examinations of sand fractions of the soils indicate that the zeolites are sub-angular to angular and highly weathered minerals. X-ray diffraction (XRD) analysis shows a strong peak at 0.90 nm of zeolites along with feldspar and quartz. Changes of phases of zeolites on thermal treatment from 0.90 nm at 25°C to 0.86 nm at 300°C and their complete disappearance at 450°C confirm that they are silica-poor and base-rich heulandite type[7,8].

The presence of smectites and zeolites made the formation of black soils possible in micro-depressions even in a tropical humid climate[7]. Zeolites were reported to play a role in the persistence of high-altitude ferruginous Alfisols in the humid tropical Western Ghats and the Satpuras in India[8,9]. Natural zeolites have helped maintain soil productivity as well as ecobalance and biodiversity of the Western Ghats for the last several millions of years[10].

The Deccan Volcanic Province (DVP) comprises a sequence of basaltic flows covering an area of nearly 0.5 M km^2 in Peninsular India. An account of the zeolites and other cavity minerals in the DVP has already been reported[11–18]. The utility of Ca-rich zeolites in Indian soils has been reported to ameliorate the bad effects of high pH, sodium, magnesium and poor drainage[1]. These zeolites have been described as the natural saviour for soils to maintain their quality[10]. The occurrence of zeolites in this area has now been expanded to other parts of the country through the recently concluded National Agricultural Innovation Project (NAIP)-sponsored project (www.geosis-naip-nbsslup.org). We have used these datasets to update our knowledge on the occurrence of Ca-rich zeolites in soils of the Indo-Gangetic Plains (IGP) and the black soil region (BSR) of India. The present study provides an overview and update on the occurrence of zeolites in these soils and describes the methodology used for their identification, characterization and mapping. This may assist researchers to develop knowledge regarding pedo-chemical reactions that are likely to help in efficient management of vast soil natural resources in India and similar terrains elsewhere.

Materials

The study area represents two important food-growing zones of the country, namely the BSR and IGP. The background information about these areas is described below.

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Black soil region

Black soils are common in the semi-arid tropics (SAT) in India, although their presence has been reported in the humid and arid bioclimates as well[4,7,19]. These are spatially associated with ferruginous soils and thus form the major soil groups of India developed from different parent materials and climates. These soils have been reported in various physiographic positions such as red soils on the hills and black soils in the valleys in Maharashtra and Madhya Pradesh[7,20,21]. Besides, they also occur in juxtaposition in Tamil Nadu, Karnataka, Maharashtra and Andhra Pradesh[22–24]. Exactly the opposite situation is found in Tamil Nadu, where red soils are in the valleys and black soils on the hills[25]. While black soils (Vertisols and their intergrades) are formed in basalts and other basic rocks[2], red soils are formed from various rock formations. Interestingly, spatially associated red and black soils can only be found in basalts, where a part of them contains amygdaloidal zeolites[7,9,11,12,26,27]. However, basalts do not contain zeolites in some other parts of the country. An account of zeolites and other cavity minerals is given by Phadke and Khirsagar[11], while their utility in soils has been detailed elsewhere[1,7–9]. The black soils (Vertisols and their intergrades)[28] represent a wide area and are potentially important crop production zones in the country. These are spread extensively in Madhya Pradesh, Gujarat, Rajasthan, Maharashtra, Andhra Pradesh, Tamil Nadu and Karnataka. Reports of Vertisols and their intergrades occur in many other states and their total area is 74.6 m ha to cover 36 agro-eco-subregions (AESRs)[19,29,30]. While selecting the soil sites, specific bioclimatic systems were identified showing variation in rainfall (mean annual rainfall (MAR, mm)).

The black soil regions in the central, western and southern parts of the country are dominated by shrink–swell soils. These soils are formed in the basaltic alluvium and are mostly deep to very deep (>150 cm), clayey with characteristic cracking clay minerals. These soils were selected from various benchmark (BM) sites[19,31].

The Indo-Gangetic Plains

The IGP ranks as one of the most extensive fluvial plains of the world. The fluvial deposits and landforms of the IGP have been influenced by the stresses directed towards north and northeast. The major rivers of the IGP have changed their courses and, at present, are flowing in the southeast and easterly directions with convexity towards the southeast[32]. Thus, the IGP shows a series of terraces, bars and meandering scars resulting in micro-high and micro-low areas on the apparently smooth topography[33,34]. The major sedimentation is still taking place from large river systems of the IGP. The plains developed mainly by the alluvium of the Indus, Yamuna, Ganga and other rivers. The nature and properties of the alluvium vary in texture, $CaCO_3$ content and acidity. Though the overall topographic situation remains fairly uniform with elevations of 150 m amsl in the Bengal basin, and 300 m amsl in the Punjab plain, local geomorphic variations are significant[35].

Methods

The methodology of the present study involves two major aspects. The first one deals with identifying BM spots with zeolitic soils in the soil map (1 : 2 m scale), while the next step deals with mapping the areas occupied by soils containing zeolites (Figure 1). Preliminary screening for the presence of zeolites in soils involves two methods as described below.

Indirect (chemical) method

Base saturation, as evidenced by the presence of calcium, magnesium, sodium and potassium, of soils exceeding 100% has been reported to be an indirect confirmation on the presence of zeolites in soils[1,7–9]. The soils were so selected that the sum of their bases is more than 100% (refs 7, 8). Presence of zeolites can indirectly be ascertained by measuring CEC of the soil. In this method, NaOAc (pH 7) was used for saturating the soils and NH_4OAc (pH 7) for exchanging the Na^+ ions; and CEC was determined by estimating the adsorbed Na^+ ions. For saturating soils, the exchange between Na^+ ions and Ca/Mg^{2+} ions of the Ca/Mg-zeolites is expected to be negligible because zeolites have less selectivity for Na^+ ions[36]. Conversely, during the determination of extractable bases by NH_4OAc, zeolites can contribute Ca^{2+} and Mg^{2+} ions by NH_4–Ca/Mg exchange, since zeolites have higher selectivity for NH_4^+ ions[36]. This is the reason why these soils containing calcium-rich zeolites have more than

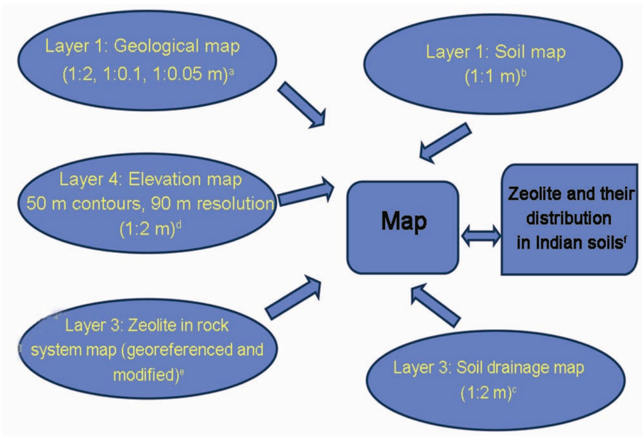


Figure 1. Schematic diagram showing the various steps for generating a distribution map of zeolites in Indian soils. [a]Mandal *et al.*[19]; [b]Staff, NBSSLUP[54]; [c]Mandal *et al.*[19] (see Figure 6); [d]Ref. 62; [e]Sabale and Vishkarma[55] (see Figure 3); [f]see Figure 3.

100% base saturation[8]. To confirm the presence of zeolites, we also used the X-ray diffraction (XRD) method. In most of the cases, the characteristic 0.90 nm peak of zeolites is reinforced on heating a K-saturated sample to 110°C, which disappears on further heating to 300–450°C, indicating the zeolites to be of the Si-poor but Ca-rich group I heulandite type (Figure 2)[7,37].

Direct (instrumental) method

This was performed using X-ray diffractograms and identifying peaks of zeolites and also using other tools like SEM and micro-morphological thin section data. Zeolites are classified into three groups, group I (Si-poor), group II (moderate) and group III (Si-rich). The type of zeolite is confirmed by the thermal behaviour of zeolite[37,38] as shown schematically in Figure 2. Once the BM soils containing zeolites were identified, this information was incorporated into the soil map using the steps explained schematically in Figure 1. The information on the presence of zeolites was ascertained by XRD analysis of different soil size separates such as, sand, silt and clay fractions from the published literature and reports[7–10,22,24,32,39–53]. Various information was utilized to generate the thematic maps showing distribution of zeolites in Indian soils. These are: (a) mapping zeolites present in the Indian rock system; (b) soil map of India (1 : 1 million scale)[54]; (c) geology map (1 : 2 million scale)[55], (d) soil drainage map of India (1 : 2 million scale)[19]; and (e) elevation (contour) map (50 m contour interval) of India[19]. These explained in the following paragraphs.

Zeolite mapping in rocks

Zeolites in rocks were reported and mapped for the western part of Maharashtra. It is interesting to note that the areas where rock systems contain zeolites are predominantly occupied by black soils which are spatially associated with red soils. All these soils are endowed with Ca-rich zeolites in sand, silt and clay fractions[7,8].

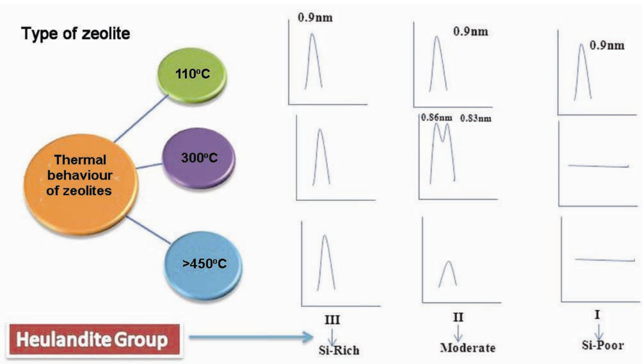


Figure 2. Identifying zeolites in soils using X-ray diffraction methods (source: Brown[37] and Bhattacharyya *et al.*[7–9]).

Soil map (1 : 1 m scale)

A three-tier approach using remote sensing and aerial photo interpretation techniques; ground truth collection and soil analysis; cartography and printing was used to generate soil map of India. Totally 1649 of soil associations (subgroups, soil taxonomy) were reported. Part of this information was used as the second layer for developing the distribution of soil zeolite map. Using the knowledge of soil zeolites (Figure 2) 51 BM spots (~300 soil horizons) in the BSR and nine BM spots (~50 soil horizons) in the IGP were used for the present study. Since the study involved analyses of sand, silt, coarse and fine clay, the total sample size was 1200 and 200 for BSR and IGP respectively, showing an overall sample frequency of ~ 14–15 per m ha.

Geology map (1 : 2 m scale)

It has been reported that amygdaloidal basalts containing zeolites are in abundance in the western part of Maharashtra[55]. Research findings carried out on soils of the BSR and IGP indicate occurrence of zeolites as well as black soils in many other states like Gujarat, Madhya Pradesh, Tamil Nadu, Karnataka, Andhra Pradesh, Uttar Pradesh and West Bengal[4,19]. Since 1 : 2 m geology map of the country was not able to provide appropriate boundaries along with the detailed geological information, we used district level (1 : 50,000 to 1 : 1 lakh) maps wherever available.

Soil drainage map (1 : 2 m scale)

Our findings in the Western Ghats of Maharashtra[7,8] and the Satpuras[9] indicate that zeolites are, by and large, abundant in the plateau, hills, inselbergs and erosional surfaces of the pediments and foothills. This is notwithstanding the fact that the zeolites are not uncommon in the valley soils formed in the basaltic and coastal alluvium. This demands exact boundary of these geomorphic surfaces, which were captured through the soil drainage map[19].

Elevation (contour) map (50 m contour)

Details of geomorphological units are well delineated by the elevation (contour map) with 90 m SRTM (Shuttle Radar Topography Mission) data. While developing the theme map on zeolites, the topography and zeolitic occurrence were given due consideration as described later.

Results

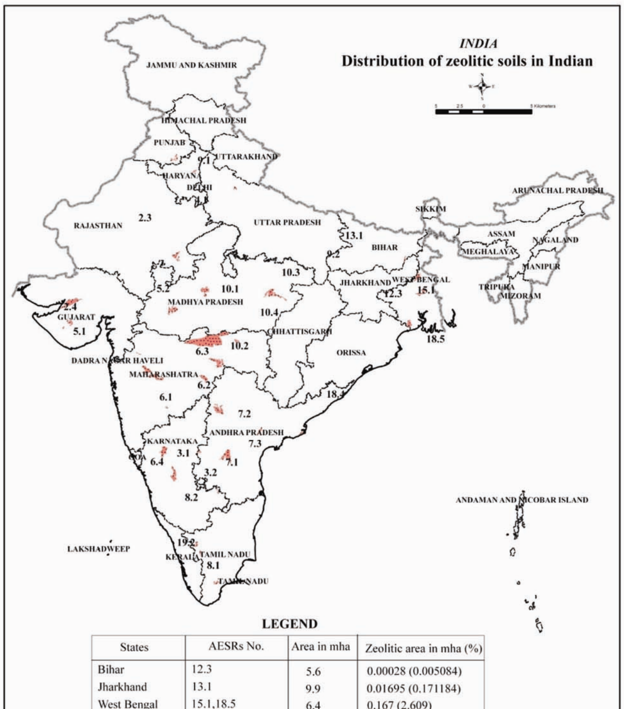
Using the various layers of map information such as geology, soil, soil drainage and elevation (contour), we generated the distribution of zeolitic soils in the IGP and BSR (Figure 3). The distribution of zeolites in the IGP and the BSR is described below.

Distribution of zeolitic soils

Zeolitic soils have been estimated to occupy ~2.8 m ha, which constitutes nearly 1% of the total geographical area of the country (Table 1). It is noted that arid and semi-arid climates constitute 86% area of the zeolitic soils in India (Table 2 and Figure 4). More than 60% area of zeolitic soils is found in Maharashtra, Madhya Pradesh and Andhra Pradesh (Figure 5 and Table 3). Seven AESRs representing five bioclimatic systems cover only 8% of the total zeolitic area in the IGP (Tables 1 and 2). The BSR occupies the remaining 92% area representing 21 AESRs and 24 bioclimatic systems (Tables 1 and 2).

Mineralogical properties of the black soils

XRD analysis indicates the dominant presence of crystalline smectite in both coarse (>50%) and fine clay (>90%) along with some non-expanding minerals like mica, chlorite, palygorskite, vermiculite and kaolin. In silt fraction



LEGEND

States	AESRs No.	Area in mha	Zeolitic area in mha (%)
Bihar	12.3	5.6	0.00028 (0.005084)
Jharkhand	13.1	9.9	0.01695 (0.171184)
West Bengal	15.1,18.5	6.4	0.167 (2.609)
Rajasthan	2.3,4.1	23.3	0.05871 (0.497558)
Uttarakhand	9.1	3.9	0.03446 (0.883646)
Uttar Pradesh	9.2	8.3	0.00074 (0.008886)
Madhya Pradesh	5.2,10.1,10.3,10.4	33.5	0.42995 (1.28342)
Maharashtra	6.1,6.2,6.3,10.2	28.4	1.20084 (4.22832)
Andhra Pradesh	3.2,7.1,7.2,7.3,18.4	22.72	0.35070 (1.54356)
Karnataka	3.1,6.4,8.2,19.2	20.36	0.23277 (1.14329)
Gujarat	2.4,5.1	8.8	0.23005 (2.61416)
Tamil Nadu	8.1	3.7	0.06942 (1.87622)

Figure 3. Distribution of zeolitic soils in India.

smectite content was less (10–20%) along with other non-expanding minerals and zeolites. In general, the fine clay smectites are hydroxy-interlayered and the extent of hydroxy-interlayering increases in soils of semi-arid and arid climates. Figures 6 and 7 show the representative X-ray diffractograms of silt and sand fractions of the BM soils studied. Ideally, zeolites are identified by the characteristic peaks in and around 0.89–0.90 nm, which on thermal treatment behave differently for identifying Ca-rich zeolites[7,8] (Figure 2). SEM studies showed typical zeolities in the selected BM sites (Figure 8). Micromorphological study showed that shrinking and swelling behaviour of these soils results in a dense groundmass exhibiting porostriated, granostriated, parallel-striated and reticulate-striated plasmic fabric. Soils of sub-humid moist climate showed strong plasma separation with parallel/cross/reticulate striated plasmic fabrics, whereas soils of sub-humid dry climate showed moderate to strong plasma separation with parallel striated plasmic fabric. Soils of semi-arid moist climate showed moderate to strong parallel striated and also stripple-speckled plasmic fabric, whereas soils of semi-arid dry climate showed crystallitic, weak cross-striated and weak reticulated and granostriated plasmic fabric. Soils of arid dry climate showed crystallitic and granostriated plasmic fabric. It was also noticed that some soils of semi-arid dry climate showed moderately strong parallel striated plasmic fabric, presumably because of their favourable hydraulic properties containing soil modifiers like zeolites and gypsum[1]. Despite a high degree of clay activity and shrink–swell process, the plasmic fabric is not uniform among the black soils of different climates.

Ca-rich zeolites in the soils of the IGP

Ca-rich zeolites were first reported in Indian soils from the Western Ghats[7]. The provenance of these zeolites is linked with the Deccan basalt, as detailed elsewhere[8]. Black soils, popularly known as black cotton soils, are usually deep to very deep and are dominated by smectitic clays. They are characterized by the presence of either slickensides or wedge-shaped peds, $\geq 30\%$ clay and cracks that open and close periodically. These soils are grouped as Vertisols[4]. A group of soils belonging to other soil orders possesses the characteristics of black soils and is often spatially associated with the Vertisols as their intergrades. This fact assumes importance because Vertisols and the vertic intergrades of soils have similar characteristics and require similar land management for agriculture and allied uses. Reports show the presence of Vertisols in the IGP[4]. While Maharashtra, Madhya Pradesh and Gujarat have the major share of black soils in the country they are also reported from Kerala, Jammu and Kashmir (J&K) and Andaman and Nicobar Islands. The occurrence of shrink–swell soils in Kerala appears to

Table 1. Distribution of zeolitic soils in the Indo-Gangetic Plains (IGP) and the black soil region (BSR) representing various agro-ecological subregions (AESRs) in India

Modified AESR no.	Bioclimate	MAR[a] (mm)	AESR[b] area (m ha)	Zeolitic soils: Area (m ha)	Zeolitic soils: % Area[c]
IGP					
2.3	Arid	300–450	11.5	0.00004	0.001
9.1	Semi-arid	700–1000	3.9	0.03446	1.234
9.2	Semi-arid	1000–1200	8.3	0.00074	0.027
12.3	Sub-humid	1200–1500	5.6	0.00028	0.010
13.1	Sub-humid	1200–1500	9.9	0.01695	0.607
15.1	Humid	1300–1600	5.2	0.13472	4.825
18.5	Per-humid	1900	1.2	0.03231	1.157
BSR					
2.4	Arid	400	6.1	0.18049	6.465
3.1	Arid	400–500	1.56	0.01907	0.683
3.2	Arid	400–500	3.02	0.00549	0.197
4.1	Semi-arid	600–800	11.8	0.05867	2.101
5.1	Semi-arid	600–700	2.7	0.04955	1.775
5.2	Semi-arid	800–1000	14.0	0.16841	6.032
6.1	Semi-arid	600–750	7.6	0.10845	3.884
6.2	Semi-arid	700–1000	12.6	0.17516	6.274
6.3	Semi-arid	800–1100	5.4	0.71253	25.521
6.4	Semi-arid	1000–1200	5.4	0.16852	6.036
7.1	Semi-arid	700–750	3.9	0.16824	6.026
7.2	Semi-arid	700–1000	9.2	0.1289	4.617
7.3	Semi-arid	800–1100	3.4	0.02787	0.998
8.1	Semi-arid	600–900	3.7	0.06942	2.486
8.2	Semi-arid	550–1000	6.5	0.0322	1.153
10.1	Humid	1000–1500	8.1	0.13458	4.820
10.2	Semi-arid	1000–1200	2.8	0.2047	7.332
10.3	Semi-arid	1000–1200	5.8	0.05822	2.085
10.4	Humid	1100–1500	5.6	0.06873	2.462
18.4	Humid	1200–1500	3.2	0.0202	0.724
19.2	Humid/per-humid	2000–3000	6.9	0.01298	0.465
	Total		174.88	2.79189	100

[a]MAR: Mean annual rainfall; [b]Source: Mandal *et al.*[19]; [c]Values show the percentage of areas occupying total zeolitic soils (~2.80 m ha) in IGP and BSR.

Table 2. Distribution of zeolitic soils in the IGP and BSR

Bioclimate	IGP: Modified AESR nos.[a]	IGP: Area in m ha (%)	BSR: AESRs	BSR: Area in m ha (%)
Arid	2.3	0.00004 (0.001)[b]	2.4, 3.1, 3.2	0.3 (7.3)
Semi-arid	9.1, 9.2	0.0352 (1.3)	4.1, 5.1, 5.2, 6.1, 6.2, 6.3, 6.4, 7.1, 7.2, 7.3, 8.1, 8.2, 10.1, 10.2, 10.3	2.4 (81.1)
Subhumid	12.3, 13.1	0.01723 (0.6)	c	c
Humid and perhumid	15.1, 18.5	0.16703 (6.0)	10.4, 18.4, 19.2	0.1 (3.6)

[a]AESR – Source: Mandal *et al.*[19]; [b]Percentage of total area under zeolitic soils (~2.8 m ha); [c]Zeolitic soils not identified in this bioclimate.

be related to the fluvial deposit by rivers. The presence of such soils in J&K may be due to the presence of basic rocks in the complex rock system in the Himalayan regions.

Studies were made on some BM soils in the upper, middle and the lower IGP[56–58]. These soils qualify for Vertisols and their intergrades[4] and their properties were found to be similar to the Vertisols in the peninsular region. The smectitic clay minerals of the Vertisols in the IGP were inherited from the alluvial parent materials and are comparable to those of the Deccan basalt areas. Geomorphic history indicates that the Damodar river in the lower IGP, like many other rivers here, was flowing in the easterly direction to meet the Bhagirathi during the middle of the 18th century[58], but has since shifted its mouth 120 km to the south. These rivers flow from west to east draining the Rajmahal Trap area which consists of 2000 ft of basaltic flows and dolerites. The rivers flowing in the vicinity of Rajmahal Trap are perennial in nature and huge amounts of smectite were formed presumably

Table 3. Distribution of zeolitic soils in different states of India

State	Modified AESRs nos.[a]	Area (m ha)	Zeolitic soils Area (m ha)	Zeolitic soils Area[b] (%)
Andhra Pradesh	18.4, 3.2, 7.1, 7.2, 7.3	22.72	0.35070	1.5436
Bihar	12.3	5.6	0.00028	0.0051
Jharkhand	13.1	9.9	0.01695	0.1712
Karnataka	19.2, 3.1, 6.4, 8.2	20.36	0.23277	1.1433
Madhya Pradesh	10.1, 10.3, 10.4, 5.2	33.5	0.42995	1.2834
Maharashtra	10.2, 6.1, 6.2, 6.3	28.4	1.20084	4.2283
Rajasthan	4.1	11.8	0.05867	0.4972
Tamil Nadu	8.1	3.7	0.06942	1.8762
Uttarakhnad	9.1	3.9	0.03446	0.8836
Uttar Pradesh	9.2	8.3	0.00074	0.0089
West Bengal	15.1, 18.5	6.4	0.16700	2.6090
Rajasthan	2.3	11.5	0.00004	0.0005
Gujarat	2.4, 5.1	8.8	0.23005	2.6142

[a]AESR – Source: Mandal *et al.*[19]; [b]Percentage of total area under zeolitic soils (~2.8 m ha).

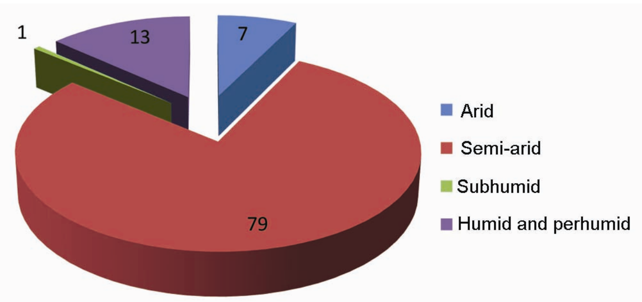


Figure 4. Distribution of zeolitic soils in India in different bioclimatic systems (values show percentage of total area of ~2.8 m ha zeolitic soils in the country).

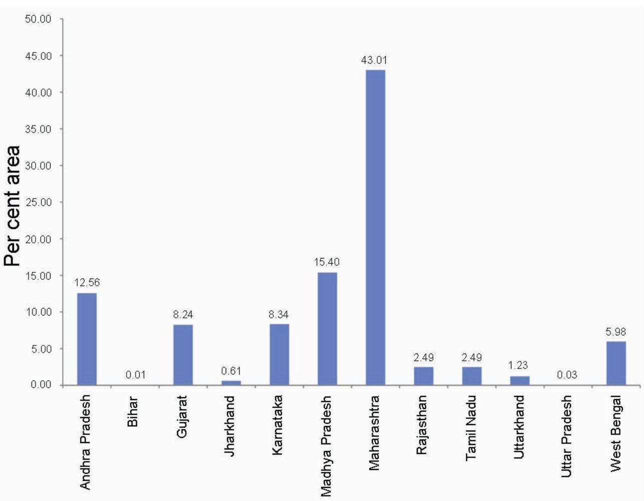


Figure 5. Distribution of zeolitic soils in different states of India (values show percentage of total area under zeolitic soils ~2.8 m ha).

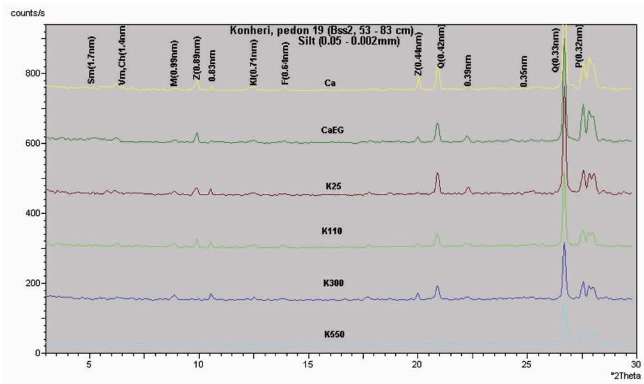


Figure 6. Representative XRD patterns of the silt fractions showing presence of zeolites in Konheri soils of semi-arid dry climate. Ca, Ca-saturated; CaEG, Ca-saturated plus glycol vapour; K25/110/300/550°C, K-saturated and heated to 25°C, 110°C, 300°C and 550°C; Sm, smectite; Vm, Vermiculite; Ch, Chlorite; M, Mica; Z, Zeolite; Kl, Kaolin; Q, quartz; F, Feldspars; P, Plagioclase.

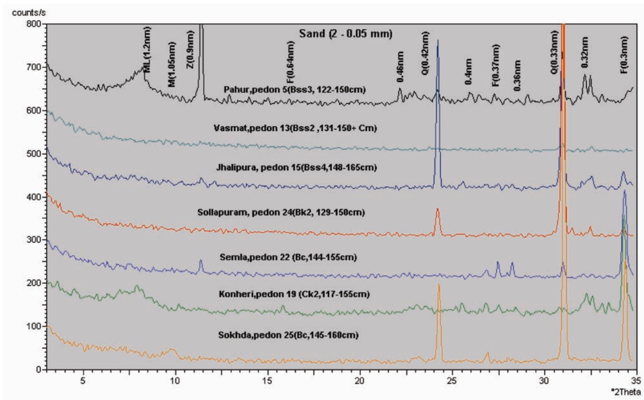


Figure 7. Representative XRD patterns of sand fractions showing presence of zeolites in Vertisols of different climatic regions. ML, Mica-vermiculite; M, mica; Z, Zeolite; Q, quartz; F, Feldspars.

due to higher rainfall in the area. Therefore, in view of the geomorphic history and similar nature of smectites between Vertisols of IGP and Deccan basalt area, it is most likely that the Vertisols in the lower IGP are developed in the smectite-rich alluvium of the Rajmahal Traps carried by the rivers which once flowed towards the east. And since most of the Ca-rich zeolitic soils are

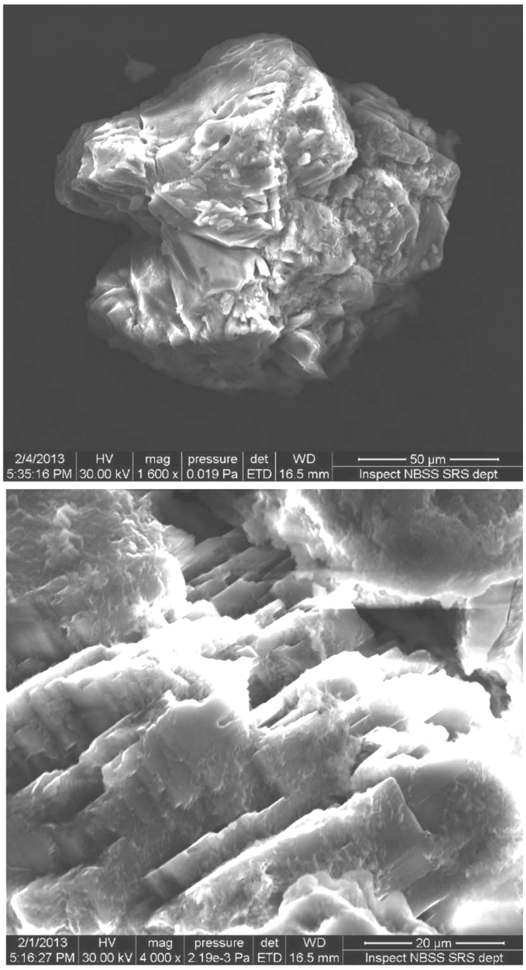


Figure 8. Representative scanning electron photomicrographs of Ca-rich zeolites from Konheri benchmark spot (Vertisols) at different magnifications.

found in the black soils, it seems probable that the source of these zeolites even in the IGP is of basaltic origin.

Application of zeolites and the map generated

Nature protects the quality of soil by continuous replenishment of bases through Ca-rich zeolites. The same technique can be utilized to maintain and improve the quality of natural resources like the soil. This requires information on the occurrence of Ca-rich zeolites in the country so that they can be a rich source of soil ameliorants. This fact assumes importance since such technology is being adopted by Gujarat farmers to add weathered basalts rich in calcium carbonate, zeolites and gypsum in the black soils grown for cultivating groundnut in and around Junagadh, Rajkot and Porbandar. This technology not only helps maintain soil health, but also makes it porous for more aeration to improve physical condition of the soils for better pegging and appreciable gain in groundnut yield[59].

The zeolitic minerals can be used as amendment for degraded black soils, wherein subsoil sodicity and pedogenic $CaCO_3$ are high. From the map showing distribution of zeolitic soils (Figure 3), feasibility study regarding proximity of hills and foothills can be ascertained. This can also indirectly help decide various land uses in terms of agriculture, horticulture and/or plantation.

Discussion

The Ca-rich zeolites have been reported to be a natural saviour against soil degradation[10]. Formation of secondary carbonate in soils has been a major factor of chemical soil degradation in arid and semi-arid climate[2]. For the prioritization of areas for conservation agriculture[4] and also for organic carbon sequestration in the semi-arid tropics[3], an area of 155.8 m ha was identified. The soil information supported by geological evidences of the presence of zeolites helped update the distribution of zeolitic soils and to generate a theme map. The zeolites are mostly concentrated in the drier tracts of the country (Table 2) and help maintain soil health against natural soil degradation[1].

The occurrence of zeolitic soils is often closely related to the topographical position of the landscape. Major landforms where zeolites seem to occur are the plateaus, upland plains and coastal plains in the Indian subcontinent[1,7,8,10]. Since zeolitic soils are better drained than the non-zeolitic soils, knowledge on soil drainage and surface run-off and related information helps in confirming occurrence of zeolites in soils[1,9]. Our observations indicate that the zeolitic soils are mostly confined in the pediments (sloping regions of the upland) of the Deccan plateau, although a few are also found along the valley floor of the BSR. In the BSR, topographical variations are common in the landform and zeolitic soils occur both in the higher and lower landforms. In the hills these occur at an elevation between 450 and 600 m amsl, in the upland between 200 to 450 m amsl and in the valley at <200 m amsl. Incidentally zeolitic soils are also reported at ~1100 m amsl in the Western Ghats and the Satpuras[1,9] in the BSR. Conversely, the zeolitic soils in the IGP occur along the drainage channels in the valley where the basaltic alluvium deposited the smectite and clay-rich black soils. The topography shows that the upper IGP, where zeolites are identified in soils, shows higher elevation, i.e. >200 m amsl. In the lower IGP, on the other hand, similar soils occur at an elevation of <50 m amsl. This suggests the utility of topographical and drainage information in the BSR and the IGP respectively, for ascertaining the occurrence of zeolitic soils.

In general, sub-soil sodicity (high exchangeable sodium per cent (ESP), in the deeper layers of soils) and presence of pedogenically formed $CaCO_3$ (PCs) are mutually inclusive. These PCs are responsible for natural chemical degradation realized in terms of impairment of hydraulic properties of soils to render these soils poorly drained. Presence of Ca-rich zeolites prevents the increase in pH to increase Ca/Mg ratio of exchange sites and improve soil drainage, even if ESP is more than 15 in the black soils of India. Therefore, these Ca-rich zeolites can help maintain better soil drainage which ultimately helps crop performance during the rainy season[1,59].

The occurrence of acidic Mollisols, Alfisols and Vertisols developed on the Deccan basalt and its alluvium in the BSR and IGP areas under humid tropical climatic conditions, provides a unique example of tropical soil formation, which is not easily comprehensible unless the role of zeolites was highlighted by the Indian soil scientists during the last two decades. Zeolitic Vertisols are being used for cultivation of rice and sugarcane because they do not remain waterlogged for a longer time and they also support winter crops. At present, these soils are mitigating the adverse effect of Holocene climate change to aridity and also sequestering carbon from the atmosphere. Experimental results obtained on the use of zeolites (other than heulandites) as soil conditioners and slow-release fertilizers provide important clues to address the possible role of soil heulandite in minimizing the conversion of NH_4^+ ions to gaseous phases of N, and adsorption and desorption of major nutrients in natural soil environments[60]. A research need was strongly felt for delineating areas under zeolitic soils and also for understanding the selective role of zeolites in the adsorption and desorption reactions of N, P and K. Updating the status of Ca-rich zeolitic soils and the generating a theme map on them at the national level are thus timely. We hope that this map will help natural resource managers in developing management practices for the efficient use of zeolitic soils for enhancing agricultural productivity under wet and dry climatic conditions[61]. This state-of-art information shall encourage the quest for newer areas of zeolitic soils to revise the present map in order to benefit various stakeholders of precious natural resources like the soil.

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ACKNOWLEDGEMENTS. Part of this study was carried out with financial assistance from the National Agricultural Innovative Project (NAIP) (Component 4) funded studies on 'Georeferenced soil information system for land use planning and monitoring soil and land quality for agriculture'. We thank Dr N. V. Chalapathi Rao for useful suggestions to improve the manuscript.

Received 15 April 2015; revised accepted 3 June 2015

doi: 10.18520/v109/i7/1305-1313